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Noise Shielding in an Agent-Based Transport Model Using Volunteered Geographic Data

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Abstract

This paper describes an improved noise modeling approach for the agent-based transport simulation MATSim. In contrast to previous versions, the new implementation takes into account the shielding of noise at building facades. The simplified approach is based on German noise modeling guidelines. As a proof of concept, a comparative calculation of noise immissions for a use case in the city of Munich with and without the consideration of buildings reveals more realistic immission values when shielding is taken into account. While uncovered areas are not affected by the updated calculation, backyards and areas behind larger building blocks show a major reduction in immissions. When looking at noise exposure costs in a dense area, ignoring the effect of shielding seems to significantly overestimate costs by up to 20%. The presented approach is a step forwards incorporating environmental aspects in an agent-based integrated land use/transport modeling suite.

Keywords: traffic noise modeling; agent-based transport simulation; MATSim

1. Introduction

Motorized transportation modes come at the cost of negative environmental effects such as noise or air pollution. A problem of these effects is that individuals causing them are not necessarily those suffering from them or paying for them. Traffic related noise can impair health and quality of life of disposed people as it causes sleep disturbances, cardiovascular diseases and tinnitus [1]. From an economic point of view, noise can decrease the value of real estate properties [2]. That is, both from a human health perspective and economic point of view, it is crucial to provide tools to assess how noise affects the environment and society. Besides measuring emissions directly at the site, computer models allow cheaper and faster estimations of transport-related impacts. They also offer the benefit of analyzing future scenarios and policies. A review of existing noise prediction models is given by Quartieri et al [3]. Usually,

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immissions at given receiver points are calculated based on the superposition of emission levels of surrounding streets or road segments (links) that are corrected by terms for distance, angle, vehicle speed and others.

The analysis of population exposures to noise may benefit from a microscopic and time-dependent model resolution. Agent-based models provide insights into population groups and even person-specific exposures. They allow to include not only residential locations and activities such as being at home but also other sensitive sites like schools, offices and hospitals [4]. In addition, a time-dependent model allows to account for the time of day (e.g. day vs. night) and exposure duration (e.g. short-term vs. long-term). A major impact on a city's *soundscape* can be attributed to buildings and their shielding effects. The road traffic noise prediction model TRANEX [5] is an example for a noise exposure computation approach which considers shielding effects of buildings. It was successfully applied to the city of London where it was found that up to 19% of the population was exposed to major traffic noise.

In this paper, an existing agent-based and time-dependent noise exposure computation approach is enhanced by incorporating shielding effects caused by barriers and buildings. It builds on the the agent-based transport simulation MATSim (Multi-Agent Transport Simulation) [6]. A proof of concept is given and a comparative calculation of noise damage costs with and without the model extension is presented.

2. Noise Modeling in MATSim

MATSim is an agent-based transport simulation that models traffic based on daily activities and trips of agents [6]. An iterative learning approach is used in which agents execute, score and adapt their travel plans. Positive scores are obtained for performing activities while traveling usually is scored negatively. Based on experienced scores of executed plans, some agents are allowed to replan by mutating an existing plan (e.g. by choosing another route). Over several iterations, a stochastic user equilibrium is approximated. MATSim is written in Java and is open-source. It offers various extension points to plug in additional functionality.
The noise modeling feature of MATSim is one of the official extensions. It has first been developed by Kaddoura et al. [4] and is based on the German Richtlinie für den Lärmschutz an Straßen [7] (RLS-90, engl.: guideline for noise protection near streets). It allows to calculate noise emissions per link and immissions for predefined receiver points.

Noise *immission* levels are calculated for a grid of receiver points and updated every time interval t. The noise superposition for a single receiver point j is

$$I_{j,t} = 10 \cdot \log_{10} \sum_i 10^{0.1 \cdot I_{i,j,t}} \quad \{I_{i,j,t} > 0\}\,, \tag{1}$$

$$I_{i,j,t} = E_{i,t} + D^d_{i,j} + D^\alpha_{i,j} - D^z_{i,j}\,, \tag{2}$$

where $I_{j,t}$ is the total noise immission level in dB(A); $I_{i,j,t}$ denotes the noise immission level in dB(A) resulting from road segment i; $D^d_{i,j}$ is the noise correction in dB(A) due to air absorption which follows the RLS-90 approach 'lange, gerade Fahrstreifen' ('long, straight lanes'), with

$$D^d_{i,j} = 15.8 - 10 \cdot \log_{10}\left(d_{i,j}\right) - 0.0142 \cdot d^{0.9}_{i,j}\,, \tag{3}$$

where $d_{i,j}$ is the shortest distance between the road segment i and the receiver point j in meters (minimally 5 meters). $D^\alpha_{i,j}$ denotes the correction for the road segment's length in dB(A) following Nielsen et al. [8], with

$$D^\alpha_{i,j} = 10 \cdot \log_{10}\left(\frac{\alpha}{180}\right)\,, \tag{4}$$

where α is the angle from receiver point j to road segment i in degrees. $D^z_{i,j}$ is the correction term which accounts for the effect of shielding that is implemented in this paper (see Sec. 3). $E_{i,t}$ are the noise emissions from road segment i in time interval t computed as

$$E_{i,t} = E^{25}_{i,t} + D^v_i\,, \tag{5}$$

where $E_{i,t}$ denotes the resulting average noise emission level in dB(A) resulting from road segment i and time interval t; and $E^{25}_{i,t}$ is the average sound level in dB(A) for a set of assumptions, i.e. a fixed distance of 25 meters, a height of 2.25 meters and a maximum speed level of 100 km/h, a smooth asphalt road surface, a gradient of less than 5%; with

$$E^{25}_{i,t} = 37.3 + 10 \cdot \log_{10}\left[M_{i,t} \cdot (1 + 0.082 \cdot p_{i,t})\right]\,, \tag{6}$$

where $M_{i,t}$ is the traffic volume; $p_{i,t}$ is the HGV share in %. D_i^v is the speed correction term which is

$$D_i^v = E_i^{car} - 37.3 + 10 \cdot \log_{10}\left[\frac{100 + (10^{0.1\cdot(E_i^{hgv} - E_i^{car})} - 1) \cdot p_{i,t}}{100 + 8.23 \cdot p_{i,t}}\right], \tag{7}$$

with

$$E_i^{car} = 27.7 + 10 \cdot \log_{10}\left[1 + (0.02 \cdot v_i^{car})^3\right] \tag{8}$$

$$E_i^{hgv} = 23.1 + 12.5 \cdot \log_{10}\left(v_i^{hgv}\right), \tag{9}$$

where v_i^{car} denotes the maximum speed level for passenger cars in kilometers per hour; and v_i^{hgv} denotes the maximum speed for HGV in kilometers per hour. Further road-related correction terms provided by the RLS-90 [7] are neglected.

For a faster computational performance and to keep the amount of required input data low, further corrections which take into account e.g. the road surface, road gradients, multiple reflections are not accounted for. Furthermore, for each receiver point, only the road segments within the range of 500 meters are considered.

For exposure analysis, noise damages can be calculated based on immissions. Therefore, activities in which agents can suffer from noise exposure have to be defined. In a next step, affected agents performing activities are mapped to their closest receiver point. A measure of exposed agents in a time bin t can be defined as

$$N_{j,t} = \sum_n \frac{a_{n,j,t}}{T} \tag{10}$$

where $N_{j,t}$ is the number of demand units that is exposed to noise at receiver point j in time interval t, n is an individual agent performing a considered activity, $a_{n,j,t}$ is the duration that n performs an activity at receiver point j in time interval t and T is the time bin size. To obtain noise damages, the exposure exceeding certain threshold values are monetarized following the German approach described in Empfehlungen für Wirtschaftlichkeitsuntersuchungen an Straßen (engl.: Recommendations for profitability analyses near roads) [9, 4]. For each receiver point j and time interval t, the resulting damage $C_{j,t}$ is calculated as

$$C_{j,t} = \begin{cases} c^T \cdot N_{j,t} \cdot 2^{0.1\cdot(I_{j,t} - I_t^{min})}, & I_{j,t} \geq I_t^{min} \\ 0, & I_{j,t} < I_t^{min} \end{cases} \tag{11}$$

where c^T is the monetary cost rate in monetary units per dB(A) that is exposed to one demand unit for the duration of T and I_t^{min} is the threshold immission level which depends on the time of day. Similar to the study by Kaddoura et al. [4], the following thresholds were used: 50 dB(A) during the day (6 a.m. to 6 p.m.); 45 db(A) during the evening (6 p.m. to 10 p.m.) and 40 dB(A) during night time (10 p.m. to 6 a.m.).

The monetary cost rate c^T is obtained by multiplying the annual cost rate c^{annual} with the time bin size T (in hours): $c^T = c^{annual} \cdot \frac{T}{(365\cdot 24)}$. As this study will only compare the relative difference in noise damages with and without the shielding correction, the annual cost rate is simply taken from Kaddoura et al. [4]. It is based on the annual cost rate proposed by the EWS, translated to an equivalent rate for 2015: $c^{annual} = 63.3\ EUR$.

3. Noise Shielding

To stay consistent with the existing noise computation approach of MATSim, the shielding correction is implemented to comply with the RLS-90. Again, only the "long, straight lane" method is considered. For each emission source that is taken into account for a receiver point, the immision $I_{i,j,t}$ is corrected by subtracting the shielding correction term $D_{i,j}^z$ (see Equation 2). According to RLS 90, $D_{i,j}^z$ is calculated as follows:

$$D_{i,j}^z = 7 \cdot lg\left[5 + \left(\frac{70 + 0.25 \cdot d_{i,j}}{1 + 0.2 \cdot z_{i,j}}\right) \cdot z_{i,j} \cdot (K_{i,j}^w)^2\right] \tag{12}$$

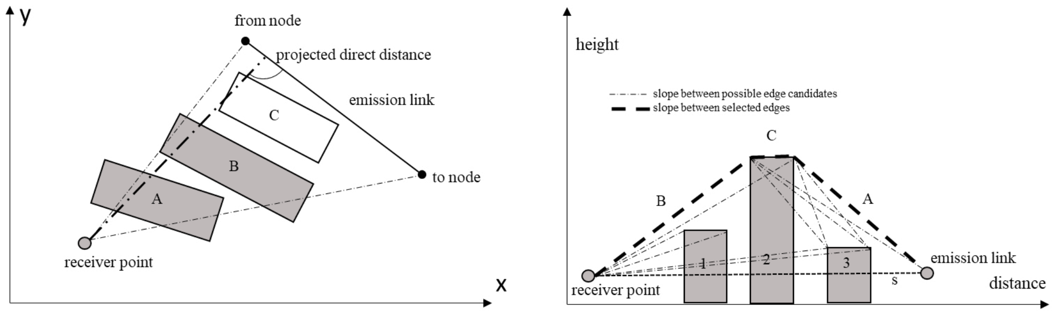

Fig. 1. The obstacles A and B are considered for shielding. Obstacle C is not obstructing the whole view and is thus not considered. View from above (left). Construction of A, B and C as the shortest path between receiver and emission source by taking into account the obstacles 1, 2 and 3 (right).

Where $z_{i,j}$ is the shielding term and $K^{w}_{i,j}$ is a weather correction. The shielding term $z_{i,j}$ is the additional distance that sound rays have to travel because of the shielding. It is obtained by adding up the distance between the emission source and first edge of diffraction $A_{i,j}$, the distance between last edge of diffraction and receiver point $B_{i,j}$ and the sum of distances between diffraction edges $C_{i,j}$ between $A_{i,j}$ and $B_{i,j}$, minus the shortest direct distance $d_{i,j}$:

$$z_{i,j} = A_{i,j} + B_{i,j} + C_{i,j} - d_{i,j} \tag{13}$$

$K^{w}_{i,j}$ is a distance dependent correction:

$$K^{w}_{i,j} = exp\left(\frac{-1}{2000}\sqrt{\frac{A_{i,j} \cdot B_{i,j} \cdot d_{i,j}}{2 \cdot z_{i,j}}}\right) \tag{14}$$

For an obstruction to be taken into account into the shielding correction, it has to overtop the direct line of sight between emission source and receiver (which is the projected shortest distance $d_{i,j}$) for at least a distance d^{u}. Otherwise, the emitting link has to be cut into smaller segments that have to be treated separately. However, since only the 'long, straight link' approach is used, this condition is simplified in this implementation: an obstruction will be taken into account only if it covers the whole view of the link from the receiver point perspective. Therefore, the algorithm will check whether the line of sights to the from and to nodes of the link as well as the shortest projected distance to the link is obstructed (see figure 1, left).

After determining all obstacles between the receiver point and the link, the shielding value $z_{i,j}$ is calculated. The height of each obstacle is assumed to be given and flat roofs are assumed. The construction of the distances $A_{i,j}$,$B_{i,j}$ and $C_{i,j}$ is a two dimensional shortest path problem around the obstacles. To solve it, all possible edges of sound diffraction are considered. Starting from the receiver point, the slopes of the connections to all following edges are calculated. The edge with the highest slope is then fixed as the next considered edge of diffraction, from which the slopes to the remaining edges are determined. This process continues until the full path between receiver point and emission link is constructed. Finally the length of the path segments are used to determine $z_{i,j}$ and the shielding correction term $D^{z}_{i,j}$. Depending on the input data, an additional preparation step is required if arrays of attached obstacles are represented as small individual polygons. In this case, obstructing elements cannot be identified as they have to obstruct the whole view between receiver point and emission link. Therefore, attached obstacles have to be dissolved into combined polygons (see figure 2). This can be done with GIS software. In this study, the average height of attached obstacles was used for the combined obstacle, which can be a limitation in cities with an uneven distribution of building heights.

4. Use Case

The improved immission modeling approach is tested in a use case for the city of Munich. Travel demand is derived from a synthetic population of the greater Munich metropolitan region. An adapted trip-based demand model called MITO (Microscopic Transport Orchestrator) [10] is used to convert the population into trips.

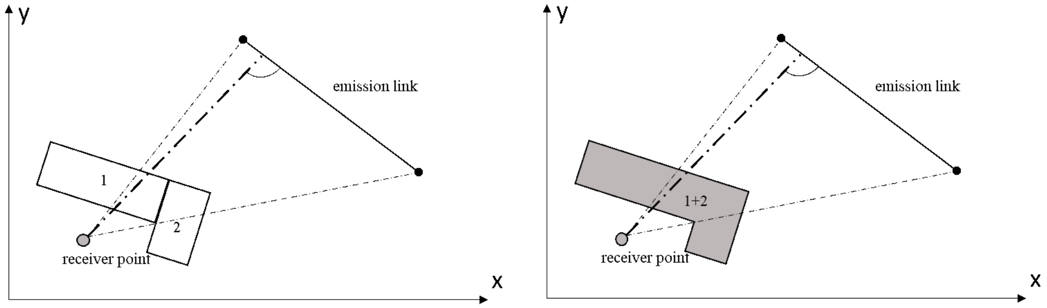

Fig. 2. Separated building polygons cannot be detected as obstructions by the implemented algorithm (left). The dissolved polygon is correctly detected to obstruct the sound propagation (right).

In total 8,725,486 trips with a car share of 43% were created. Given the current limitations of MITO, freight trips were not included. The synthetic population features microscopic dwelling locations for households that refer to residential building locations of OpenStreetMap (OSM, www.osm.org). A five percent population sample was converted into MATSim agents. The network was converted from OSM data and contains a fine network for Munich and more coarse connections to the surrounding areas.

Building data were provided by OsmBuildings [11]. They include a dump of all objects that are identified as buildings in OSM for Munich. After dissolving attached polygons, the data set consists of 160,490 features. Height information of buildings is partially given by the 'height' OSM tag (1,286 cases). More common, the number of levels is given in OSM where an average height of 3.5 meters per level was assumed (20,394 cases). Where no height data were available, an average building height of 10 meters was used. The receiver point grid was defined with a spacing of roughly 15 meter in x and y direction. A fine grid is necessary to capture the effect of shielding in backyards. To save computation time, the grid does not cover the whole city of Munich but a larger area in the inner city. The grid is roughly 10 kilometers from East to West and 5 kilometers from North to South. In total, about 225,000 receiver points were evaluated.

As a proof of concept, figure 3 shows a comparison of simulated noise immission values expressed as the L_{DEN} value (day-evening-night index) for the inner city of Munich (part of the full receiver point grid). The building polygons are visualized on top. On the left side the immissions are shown without taking into account the shielding correction and mostly decrease with the distance to roads. On the right side, the shielding correction described in Sec. 3 is included. Taking into consideration the effect of shielding yields a major reduction in noise levels in most of the backyards. In addition, larger areas behind buildings are 'shadowed' and thus show a reduction of immissions. As expected, unobstructed receiver points (e.g. close to the roads) do not seem to be affected by shielding. Some smaller areas might lack an expected noise reduction because of the simplification of only taking fully obstructed polygons into account. Overall, the results confirm the functionality of the implemented shielding correction feature.

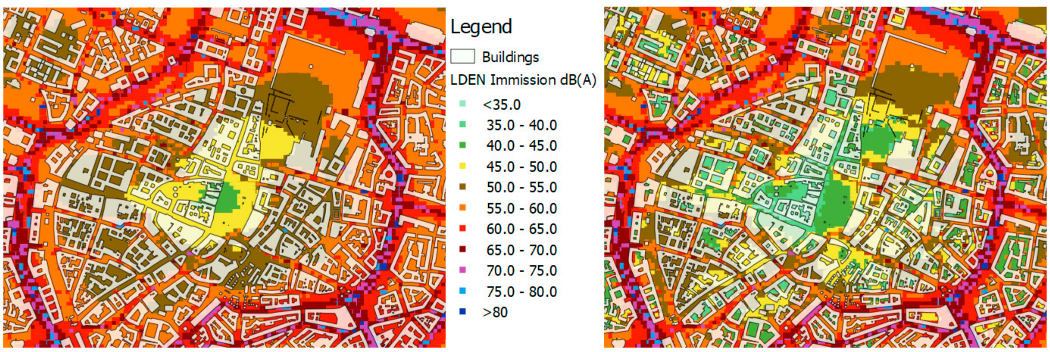

Fig. 3. Immission L_{DEN} levels before (left) and after (right) taking shielding into account. While unprotected areas remain the same, covered areas and backyards of building blocks show a major reduction of noise.

In a next step, noise exposure costs were analyzed by using equation 11 and adding up costs at all receiver points. As dwelling locations were mapped to OSM buildings, only 'home' activities were taken into account for the exposure analysis to obtain a more realistic distribution of activity locations. Without shielding correction, daily exposure costs (or noise damages) amount to 1,945.36 EUR. When taking into account the effect of shielding, the noise damages decrease to 1,555.69 EUR. This indicates that in densely populated urban areas, a noise exposure analysis which neglects the effect of shielding may overestimate the damages by up to 20%.

5. Conclusion

The effect of shielding was successfully added to an existing noise prediction model of an agent-based transport simulation. It is shown that open source building data can be used for modeling noise shielding. As expected, the improved noise computation methodology yields reduced noise levels in backyards and behind larger buildings. The comparative exposure analysis reveals a significant overestimation of noise damage costs when shielding effects of buildings are neglected. As OSM data do not provide complete information about building heights, more comprehensive data sources may improve the model accuracy. A future model extension may add the *reflection* correction term of the RLS-90 guideline to the model, which is expected to increase noise levels at urban building facades facing the street. The impact of shielding effects on exposure analysis may be analyzed in more detail by looking at further noise sensitive activity types such as education or office activities. The presented noise model will be part of an agent-based land use/transportation modeling suite that is currently under development [12]. In this suite, noise will be accounted for when updating rent prices and relocation choices. Noise exposure analysis will be used to assess environmental equity issues.

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